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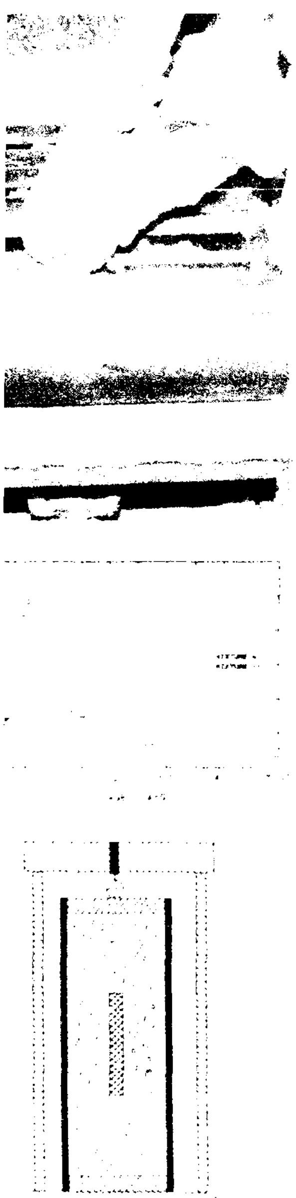

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CONCRETE MIXTURE SELECTION AND CHARACTERIZATION STUDY OLMSTED LOCKS AND DAM, OHIO RIVER

by

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13. ABSTRACT *(Maximum 200 words)*

This report documents a mixture proportioning investigation and complete thermal and mechanical properties study of potential concrete mixtures for use in constructing the Olmsted Locks and Dam on the Ohio River. The work was intended to support incremental construction analyses of the proposed structure and answer certain key questions about the feasibility of constructing a W-frame lock structure. A matrix of 12 concrete mixtures using Class C fly ash in amounts of up to 50 percent and Class F fly ash in amounts of up to 40 percent of the cementitous materials was proportioned and batched in the laboratory. From this matrix two mixtures, one with Class C and one with Class F fly ash, were selected based upon compressive strength requirements, economy, and thermal considerations for complete thermal and mechanical characterization. Tests included compressive strength and modulus of elasticity as a function of time, creep, shrinkage, specific heat, thermal diffusivity, coefficient of linear thermal expansion, and thermal conductivity. The results of these tests were analyzed and used to calibrate a time-dependent, visco-elastic material model for concrete to be implemented in a general-purpose, finite-element code.

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PREFACE

The investigation described in this report was conducted for the US Army Engineer District, Louisville. Authorization was given by DD Form 448, MIPR No. RM-B-90-122, dated 25 Oct 1989. Funds for publication of this report were provided by the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 89.

The investigation was performed at the US Army Engineer Waterways Experiment Station (WES) by personnel of the Structures Laboratory (SL), under the general supervision of Messrs. Bryant Mather, Chief, and J. T. Ballard, Assistant Chief. Direct supervision was provided by Mr. K. L. Saucier, Chief, Concrete Technology Division (CTD), and Mr. Steven A. Ragan, Chief, Engineering Mechanics Branch (EMB). Project management was provided by Mr. Michael I. Hammons, Group Leader, Applied Mechanics Group (AMG), EMB, CTD. This report was prepared by Messrs. Hammons, Billy D. Neeley, A. Michel Alexander, and Anthony Bombich, EMB, and Ms. Sharon B. Garner, Structural Mechanics Division. The authors acknowledge Messrs. Donald M. Smith, Dan Wilson, Brent Lamb, James Shirley, and Ms. Linda Mayfield, AMG, for their help during this investigation. The authors also acknowledge the assistance of Dr. Lillian Wakeley, Dr. Toy Poole, and Messrs. Michael Lloyd, Percy Collins, Tom Lee, and Julies Mason, CTD.

Commander and Director of WES is COL Larry B. Fulton, EN. Technical Director is Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Btu (International Table) per pound (mass) · degree Fahrenheit	4,186.800	joules per kilogram kelvin
Btu (International Table) feet per hour · square foot · degree Fahrenheit	1.73073	watts per metre kelvin
Btu (International Table) per hour · square foot · degree Fahrenheit	5.67826	watts per square metre kelvin
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048000	metres
inches	25.40000	millimetres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

* To obtain a Celsius (C) temperature reading from a Fahrenheit (F) reading, use the following formula: C + (5/9)(F - 32). To obtain a Kelvin (K) reading, use K = (5/9)(F - 32) + 273.15.

CONCRETE MIXTURE SELECTION AND CHARACTERIZATION STUDY
OLMSTED LOCKS AND DAM, OHIO RIVER

PART I: INTRODUCTION

Background

1. The US Army Engineer District, Louisville, is planning to replace Locks and Dams 52 and 53 on the Ohio River with a single structure referred to as the Olmsted Lock and Dam. The lock is designed as a pile-founded, W-frame structure with two parallel lock chambers. The lock monoliths are approximately 80 ft long by 320 ft wide. The central wall between the monoliths is approximately 50 ft wide. Although the Corps of Engineers has much experience in the construction of U-frame lock structures, the size and design of the Olmsted structure raises questions about potential construction problems for such a massive W-frame structure.

2. In order to answer some of these questions, the Louisville District tasked the US Army Engineer Waterways Experiment Station to conduct incremental construction and earthquake analyses of the structure. This investigation was carried out in three phases:

a. Phase I. A materials study, mixture proportioning investigation, and complete thermal and mechanical properties study of potential concrete mixtures were included in Phase I. This phase of the work was funded by the Geotechnical Branch, Engineering Division, Louisville District and conducted by the Concrete Technology Division, Structures Laboratory, US Army Engineer Waterways Experiment Station (WES).

b. Phase II. A series of incremental construction analyses were conducted in Phase II. These analyses were funded by the Design Branch, Engineering Division, Louisville District and were conducted as a joint effort by the Concrete Technology Division and Structural Mechanics Division, Structures Laboratory, and the Computer-Aided Engineering Division, Information Technology Laboratory, WES.

c. Phase III. This phase included an earthquake analysis funded by the Design Branch, Engineering Division, Louisville District, conducted by the Structural Mechanics Division, Structures Laboratory, WES.

3. This report contains the results of Phase I of the work listed above.

Objectives

4. The primary objectives of this research program were as follows:

- a. To determine the chemical and physical properties of potential cements and pozzolans and to establish baseline performance data on mortar and paste specimens for relative comparisons among candidate materials.
- b. To develop a matrix of trial concrete mixtures for laboratory evaluation. The mixtures were to be proportioned and batched in the laboratory and be subjected to selected tests on the fresh and hardened concrete. Based upon this information and the projected cost of the concrete mixtures, two concrete mixtures were selected for complete thermal and mechanical properties evaluation.
- c. To conduct thermal and mechanical properties tests on two concrete mixtures: one with a Class C fly ash and one with a Class F fly ash. The tests conducted were those needed for evaluation of the concrete materials and to yield input data for incremental construction analyses in support of Phase II above.
- d. To calibrate the aging visco-elastic material model UMAT for use in the incremental construction analyses in support of Phase II above.

Scope

5. Although project materials for the construction of the Olmsted Locks and Dam were not known at the beginning of this study, candidate cement, pozzolans, and aggregates were chosen by the Louisville District. These materials were judged (based upon a knowledge of available sources of materials) to be similar to materials likely to be chosen by a contractor for construction of the structure. Therefore, results of this study were to provide general material and thermal properties information to be used by the District to evaluate potential materials, prepare specifications, and to provide input for incremental construction analyses.

PART II: MATERIALS CHARACTERIZATION

General

6. The materials used in this investigation were selected by the Geotechnical Branch, Engineering Division, US Army Engineer District, Louisville. These materials were considered to be typical of those which might be chosen by a contractor for construction of the structure based upon a knowledge of potential sources of cementitious materials and aggregates in the vicinity of the proposed project site. A brief discussion of the materials is given below.

Cementitious Materials

7. At the outset of this project, one portland cement and four candidate fly ashes were selected by the Louisville District. The cement chosen for this study was a Type II, low alkali (LA) ASTM C 150 (ASTM, 1990) portland cement meeting the optional requirement for heat of hydration (HH) at 7 days. Chemical and physical properties of this cement are shown in Table 1. One of the candidate fly ashes was an ASTM C 618 (ASTM, 1990) Class C fly ash; the other three were ASTM C 618 Class F fly ashes.

8. A complete study of comparison of strength development and heat of hydration among the four fly ashes was carried out and has been reported (Poole, Sykes, and Griffin, 1990). Tests were conducted on mortar and paste specimens. Although properties developed from tests on mortar or paste specimens are not directly translatable into concrete properties, they are useful for relative comparisons among candidate materials without the expense of making trial batches of concrete in the laboratory. The tests conducted and the results obtained are summarized below.

9. Class C fly ash was used in proportions of 25, 30, 35, and 45 percent by solid volume of the cementitious materials. The Class F fly ashes were used as 30 percent of the cementitious materials. Control specimens (no fly ash) were also prepared. Compressive strengths were measured at 2, 7, 28, and 90 days. Heat-of-hydration tests were conducted in accordance with ASTM C 186 (ASTM, 1990) at 2, 7, and 28 days.

Table 1
Chemical and Physical Properties of Cement

Company: Lone Star Industries
Location: Cape Girardeau, MO
Specification: ASTM C 150,II,LA,FS,HH
Contract No.:
Project: Olmsted Lock & Dam

Test Report No.: REC-291-90
Program: Single Sample
CTD No.: ORL-5, C-1

10/12/90 Tests complete, material X does, ____ does not meet specification

	Result	Spec Limits "Type II"
Chemical Analysis		
SiO_2, %	23.1	20.0 min
Al_2O_3, %	3.2	6.0 max
Fe_2O_3, %	3.5	6.0 max
CaO, %	61.6	-
MgO, %	4.4	6.0 max
SO_3, %	2.2	3.0 max
Loss on ignition, %	0.7	3.0 max
Insoluble residue, %	0.17	0.75 max
Na_2O, %	0.06	-
K_2O, %	0.66	-
Alkalies-total as Na_2O,%	0.49	0.60 max
TiO_2, %	0.19	-
P_2O_5, %	0.10	-
C_3A, %	3	8 max
C_3S, %	41	-
C_2S, %	36	-
C_4AF, %	11	-
Physical Tests		
Heat of hydration, 7-day, cal/g	61	70 max
Surface area, m^2/kg (air permeability)	317	280 min
Autoclave expansion, %	0.17	0.80 max
Initial set, min. (Gillmore)	160	60 min
Final set, min. (Gillmore)	195	600 max
Air content, %	9	12 max
Compressive strength, 3-day, psi	1750	1500,1000[a]min
Compressive strength, 7-day, psi	2520	2500,1700[a]min
False set (final penetration), %	125	50 min

REMARKS: [a]Applies only to heat of hydration cement.

10. The major results of this research were the following:

- *a*. In general, Class F mixtures developed strength much more slowly than either Class C or control mixtures. Class C mixtures were slower in strength gain than control at very early ages, but faster than control at later ages. From very early ages, the mortars containing Class C fly ash steadily gained strength with respect to control, while the mortars containing Class F fly ash tended to exhibit an inactive period from 2 to 7 days.
- *b*. The use of Class F fly ash consistently reduced the heat of hydration up to 28 days compared to the control. The Class C fly ash showed a reduction in heat of hydration comparable to the Class F fly ash at 2 days. However, no reduction in the heat of hydration at 7 days (compared with the control) was observed with Class C fly ash at levels of 25 to 35 percent. However, at the 45-percent level, the heat of hydration was reduced at both 7 and 28 days.
- *c*. Early-age strength and heat of hydration varied linearly with percent replacement.

11. Based upon these findings, Louisville District, Ohio River Division, and WES materials engineers agreed upon two fly ashes for use in the mixture proportioning and thermal and mechanical properties testing phases of this investigation: the Class C fly ash and one of the Class F fly ashes tested in the mortar and paste testing. Chemical and physical properties of these fly ashes are given in Tables 2 and 3, respectively.

Aggregates

12. Basic characterization tests on the aggregates used in this study were performed at WES. These tests include grading, bulk specific gravity, and percent absorption. The results of these tests are summarized below.

13. All coarse aggregates were limestone aggregates from Dravo 3-Rivers Quarry, Smithland, Kentucky. The fine aggregate was a natural river sand from Delta Materials, Mound City, Illinois.

14. The bulk specific gravity and percent absorption of the aggregates were determined in accordance with CRD-C 107 and CRD-C 108 (US Army Corps of Engineers, 1949). The results of these tests are given in Table 4.

Table 2
Chemical and Physical Properties of Class C Fly Ash

Company: Indiana Michigan Power
Location: Rockport, Indiana
Specification: ASTM C 618, Class C
Contract No.: unknown
Project: Olmsted Dam

Test Report No.: ORL-231C-89
Program: Single Sample
CTD No.:
Job No.:
Date Sampled: unknown

11/2/89 Partial test result

12/12/89 Tests complete, material _X_ does, ___ does not meet specification

	RESULT	RETEST	SPEC LIMITS "Class C"
Chemical Analysis			
SiO_2, %	43.2		-
Al_2O_3, %	18.2		-
Fe_2O_3, %	7.3		-
Sum, %	68.6		50.0 min
CaO, %	-		-
R Factor	-		a
MgO, %	4.4		-
SO_3, %	1.5		5.0,4.0[a] max
Moisture content, %	0.0		3.0 max
Loss on ignition, %	0.4		6.0,2.5[a] max
Available alkalies (28-day), %	1.1		1.5 max
Physical Tests			
Fineness (45 micrometre), % retained	25		34 max
Fineness variation, %	-		5 max
Water requirement, %	91		105 max
Density, Mg/m^3	2.65		-
Density variation, %	-		5 max
Autoclave expansion, %	-0.07		0.80 max
Pozzolanic activity w/cement (28-day), %	119		75 min

Laboratory cement used: Lone Star Industries, Cape Girardeau, MO
Laboratory lime used: Chemstone

REMARKS: [a]Only applies to Bureau of Reclamation projects.

Table 3
Chemical and Physical Characteristics of Class F Fly Ash

Company: American Fly Ash	Test Report No.: ORL-232F-89
Location: Baldwin, Illinois	Program: Single Sample
Specification: ASTM C 618, Class F	CTD No.:
Contract No.: unknown	Job No.:
Project: Olmsted Dam	Date Sampled: unknown

11/2/89 Partial test result

12/12/89 Tests complete, material X does, ____ does not meet specification

	RESULT	RETEST	SPEC LIMITS "Class F"
Chemical Analysis			
SiO_2, %	55.7		-
Al_2O_3, %	18.8		-
Fe_2O_3, %	16.1		-
Sum, %	90.7		70.0 min
CaO, %	-		-
R Factor	-		a
MgO, %	1.0		-
SO_3, %	1.1		5.0,4.0[a] max
Moisture content, %	0.1		3.0 max
Loss on ignition, %	1.2		6.0,2.5[a] max
Available alkalies (28-day), %	0.8		1.5 max
Physical Tests			
Fineness (45 micrometre), % retained	22		34 max
Fineness variation, %	1		5 max
Water requirement, %	96		105 max
Density, Mg/m^3	2.35		-
Density variation, %	1		5 max
Autoclave expansion, %	0.02		0.80 max
Pozzolanic activity w/lime, psi	1110		800,900[b] min
Pozzolanic activity w/cement (28-day), %	106		75 min

Laboratory cement used: Lone Star Industries, Cape Girardeau, MO
Laboratory lime used: Chemstone

REMARKS: [a]Only applies to Bureau of Reclamation projects.
[b]Corps of Engineers specification.

Table 4
Aggregate Data

Aggregate	Type	Bulk Specific Gravity, S.S.D.	Absorption, percent
Coarse Aggregate (A)	Limestone	2.65	1.6
Coarse Aggregate (B)	Limestone	2.67	1.4
Coarse Aggregate (C)	Limestone	2.67	1.7
Fine Aggregate (Blended Sand)	Natural Sand	2.57	1.2

15. The gradings of the aggregates were determined in accordance with CRD-C 103 (US Army Corps of Engineers, 1949). The results of these tests are given in Table 5. The gradings of the coarse aggregates fall within the limits of the aggregate gradings in CW-03305, "Civil Works Construction Guide Specification for Mass Concrete." However, the fine aggregate furnished to WES did not meet the CW-03305 gradings due to a deficiency in fines. Thus, a filler sand was blended with the fine aggregates to alleviate the deficiencies. The gradings of the fine aggregate, filler sand, and blended sand are shown in Table 5. The grading of the blended sand meets the CW-03305 requirements.

Table 5

Aggregate Gradings (CRD - C 103)

Sieve Size	Cumulative Percent Passing					
	Coarse Agg. (A)	Coarse Agg. (B)	Coarse Agg. (C)	Fine Agg.	Filler Sand	Blended Sand
75.0 mm (3 in.)	100					
50.0 mm (2 in.)	41					
37.5 mm (1-1/2 in.)	7	91				
25.0 mm (1 in.)	2	22				
19.0 mm (3/4 in.)		3	93			
12.5 mm (1/2 in.)		2	58			
9.5 mm (3/8 in.)		2	32			
4.75 mm (# 4)			4	98		99
2.36 mm (# 8)				80		82
1.18 mm (# 16)				66	100	68
600 μm (# 30)				53	89	56
300 μm (# 50)				19	78	24
150 μm (# 100)				3	31	6
75 μm (# 200)					14	1

PART III: MIXTURE PROPORTIONS SELECTION

Project Requirements

16. The major considerations in the selection of mixture proportions for a mass concrete structure are strength, durability, heat generation, and placability. The specific requirements for this study were set by the Louisville District. These requirements are discussed below.

Strength

17. For this investigation, a project design strength requirement of 3,000 psi at 120 days was assumed. Because the lock structure is a highly reinforced W-frame structure and is a combination of mass and structural concrete, an average compressive strength of 3,900 psi at 120 days was required for the mixture proportions.

18. In addition to design strength requirements, a strength requirement of 500 psi at time of erection of the forms for the next lift (typically approximately 2 days) has traditionally been necessary for constructibility considerations. This requirement is based upon form-anchorage requirements. At strengths of less that 500 psi, special formwork anchorages may be required, thus increasing construction effort and corresponding costs.

Durability

19. Durability is the capacity of concrete to resist the processes of deterioration including freezing and thawing or other weathering action, abrasion, chemical attack, etc. The durability of the concrete is enhanced by requiring the use of a low water-cement ratio and air entrainment. Water-cement ratios varying from 0.40 to 0.50 were used for this investigation. Air contents were required to be at least 9 percent in the mortar (5 to 7 percent in the less than 1-1/2-in.-maximum-nominal-size, wet-sieved concrete).

Heat Generation

20. Early heat generation will be limited through the use of reduced quantities of cementitious materials, through the use of moderate heat cement, and through the replacement of cement with Class C or F fly ash.

Placability

21. The placeability of concrete is determined by its workability and consistency. The concrete must have enough workability to be placed,

consolidated, and finished properly without harmful segregation. The ease with which the concrete will flow during placement is its consistency. Consistency is measured by the slump of the fresh concrete as determined in accordance with ASTM C 143 (ASTM, 1989). The average slump for mass concrete should be approximately 2 in.

Preliminary Mixtures

22. Based upon the stated requirements, a matrix of 12 preliminary mixtures was established. This matrix is shown in Table 6. The matrix included water-cement ratios ranging from a minimum of 0.40 to a maximum of 0.50 based on a mass of portland cement having an absolute volume equivalent to that of the cementitious materials in the mixtures. The ratios (by volume)

Table 6

Matrix of Trial Mixtures

Mixture	Type of Fly Ash	Ratio of Fly Ash to Total Cementitious Materials, percent	Water-Cement Ratio	Total Theoretical Cementitious Materials		Estimated Cost of Cementitious Materials, $/yd^3$
				lb/yd^3	94-lb Bag Equivalents	
1	F	30	0.50	290	3.09	7.35
2	F	30	0.45	315	3.35	8.00
3	F	30	0.40	350	3.72	8.86
4	F	40	0.50	284	3.02	6.51
5	F	40	0.45	316	3.36	7.22
6	F	40	0.40	360	3.83	8.25
7	C	40	0.50	288	3.06	6.95
8	C	40	0.45	320	3.40	7.73
9	C	40	0.45	357	3.80	8.61
10	C	50	0.50	288	3.06	6.34
11	C	50	0.45	318	3.38	7.01
12	C	50	0.40	360	3.83	7.93

of fly ash to total cementitious materials (F/C+F ratio) were varied from a minimum of 30 percent to a maximum of 40 percent for the Class F fly ash and from a minimum of 40 percent to a maximum of 50 percent for the Class C fly ash. Mixture proportions for the 12 mixtures are tabulated in Table 7.

23. As with any mixture proportioning study, due consideration was given to the economy of the mixtures. The estimated cost of cementitious materials and admixtures was calculated based upon current prices for materials at potential project material sources. This information is shown in Table 6. Aggregate costs were not available for inclusion in this estimate. However, these costs should be relatively constant for all mixtures and therefore should not significantly change the ranking of the mixtures.

24. Mixtures 1 through 12 were prepared in the laboratory in accordance with ASTM C 192 (ASTM, 1989). Tests were conducted on the fresh concrete to determine slump (ASTM C 143), unit weight in accordance with ASTM C 138, and air content (ASTM C 231). Cylindrical specimens (6 by 12 in.) were prepared according to ASTM C 192 and cured in a moist curing room meeting the specifications of ASTM C 511 until time of testing. Three cylindrical specimens were tested in unconfined compression at ages of 2, 7, 14, 28, 90 and 120 days in accordance with ASTM C 39.

25. The results of the tests on the fresh concrete tests are tabulated in Table 8. Because one of the primary objectives of this study was to proportion concrete mixtures to limit heat generation, it follows that the cementitious materials content of the mixtures should be as low as possible. As the cementitious materials content decreases, it becomes increasingly critical to have properly graded aggregates in order to have mixtures with adequate workability. Also, the potential for reduced workability will be intensified if the nominal maximum size aggregate is reduced. It is possible that concrete mixtures with cementitious contents as low as some of the mixtures in this study would not have adequate workability to be placed by all available techniques if the aggregates were 1-1/2 in. nominal maximum size. However, all mixtures developed in this study have adequate workability.

Table 7

Mixture Proportions

Item or Material	Saturated, Surface Dry, Conditions per 1 Cubic Yard Batch											
	1	2	3	4	5	6	7	8	9	10	11	12
Water-Cement Ratio	0.50	0.45	0.40	0.50	0.45	0.40	0.50	0.45	0.40	0.50	0.45	0.40
F/(C+F), percent	30	30	30	40	40	40	40	40	40	50	50	50
Theoretical Cementitious Materials in 94-lb Bag Equivalents (by volume)	3.08	3.36	3.72	3.02	3.36	3.83	3.06	3.40	3.80	3.06	3.38	3.83
Type II, HH, Cement, lb	202.9	220.8	245.0	170.4	189.4	215.9	172.8	192.0	214.4	144.0	159.0	180.0
Class C Fly Ash, lb	0.0	0.0	0.0	0.0	0.0	0.0	96.9	107.7	120.3	121.1	133.7	151.4
Class F Fly Ash, lb	64.9	70.6	78.3	84.7	94.2	107.4	0.0	0.0	0.0	0.0	0.0	0.0
Fine Aggregate, lb	1046.7	1026.5	1003.6	1050.5	1042.8	998.3	1049.0	1023.9	999.6	1047.9	1025.3	998.3
Coarse Aggregate (A), lb	695.8	698.2	698.7	698.2	693.1	695.0	696.5	696.5	695.9	696.5	697.4	695.0
Coarse Aggregate (B), lb	546.7	548.6	549.0	548.6	544.6	546.1	543.2	547.2	546.8	547.3	547.9	546.1
Coarse Aggregate (C), lb	1233.1	1237.4	1238.2	1237.4	1228.4	1231.8	1234.4	1234.4	1233.4	1234.4	1235.9	1231.8
Filler, lb	79.7	78.2	76.4	80.0	79.3	76.0	79.8	77.9	76.1	79.9	78.1	76.0
Air-Entraining Admixture, oz	9.6	10.8	12.3	9.7	11.3	13.6	7.6	8.4	9.0	7.2	8.5	9.9
Water, lb	145.0	142.0	140.0	142.0	142.0	144.0	144.0	144.0	143.0	144.0	143.0	144.0

Table 8
Results of Tests on Fresh Concrete

Mixture	Type of Fly Ash	Ratio of Fly Ash to Total Cementitious Materials, percent	Water-Cement Ratio	Slump, in.	Unit Weight, pcf	Air Content in Wet Sieved Mix (< 1-1/2 in.), percent
1	F	30	0.50	3	144.0	6.4
2	F	30	0.45	2-3/4	146.4	6.4
3	F	30	0.40	2-1/4	146.4	6.2
4	F	40	0.50	2-1/2	146.8	6.2
5	F	40	0.45	1-1/2	147.4	6.1
6	F	40	0.40	2-1/4	146.0	6.1
7	C	40	0.50	2-1/4	145.0	7.1
8	C	40	0.45	2-1/2	146.2	7.1
9	C	40	0.40	2	147.8	6.0
10	C	50	0.50	2-1/2	147.8	6.2
11	C	50	0.45	2-1/4	146.2	6.5
12	C	50	0.40	2	146.8	6.6

Final Mixture Selection

26. The results of the unconfined compression tests are shown in Table 9. These data were used to select two mixtures, one with Class C fly ash and one with Class F fly ash, for complete thermal and mechanical properties characterization. The rationale used to select the two final mixtures is given below.

Class F Mixture

27. Recall that the required average compressive strength at 120 days was selected as 3,900 psi and that the compressive strength at 2 days was required to be at least 500 psi. Using these criteria Mixtures 1, 2, and 4 can be eliminated. Mixtures 3, 5, and 6 have sufficient strength at 2 days to meet the early-time strength requirement of 500 psi. Therefore, considerations of economy lead to the selection of Mixture 5 over Mixtures 3 and 6.

Table 9. Compressive Strength of Trial Mixtures

Mixture	Type of Fly Ash	F/(C+F), percent	Estimated Cost of Cementitious Materials, $\$/yd^3$	W/C Ratio	Compressive Strength, psi					
					2 d	7 d	14 d	28 d	90 d	120 d
1	F	30	7.35	0.50	640	1090	1530	2270	3190	3530
2	F	30	8.00	0.45	690	1330	1840	2390	3610	3710
3	F	30	8.86	0.40	860	1610	2420	3240	4150	4280
4	F	40	6.51	0.50	430	910	1290	1880	2880	3240
5	F	40	7.22	0.45	670	1130	1740	2530	3580	3880
6	F	40	8.25	0.40	820	1430	2110	2970	4300	4430
7	C	40	6.95	0.50	580	1350	1980	2980	3520	3860
8	C	40	7.73	0.45	730	1630	2390	3330	4240	4220
9	C	40	8.61	0.40	950	2290	3310	4120	4790	5270
10	C	50	6.34	0.50	500	1330	1830	2690	4020	4370
11	C	50	7.01	0.45	750	2070	2480	3580	4500	4720
12	C	50	7.93	0.40	910	2500	3050	4180	4790	5040

However, because of the relatively low heat of hydration (61 cal/g at 7 days compared to a maximum allowable of 70 cal/g at 7 days) of the particular cement used for this study, Mixture 6 was chosen as the Class F mixture for full thermal and mechanical properties testing. This choice was conservative, since Mixture 6 is a richer mixture than Mixture 5 and should generate more heat.

Class C Mixture

28. Similarly, Mixture 7 can be eliminated because of low compressive strength at 120 days. Mixtures 9 and 12 can be eliminated because of excessive strengths at 120 days coupled with relatively high cost of cementitious materials, leaving Mixtures 8, 10, and 11 for further consideration. Using considerations of economy, Mixture 10 was chosen over Mixtures 8 and 11. However, as described for the Class F mixture, because of the relatively low heat of hydration of the cement used in this study, Mixture 11, a richer mixture, was selected as the Class C mixture for further testing.

PART IV: MECHANICAL AND THERMAL PROPERTIES

General

29. The calibration and verification of the thermal and time-dependent material models used in the finite-element incremental-construction analyses require the knowledge of certain key material response parameters. A series of mechanical and thermal properties tests was conducted on two concrete mixtures:

a. Mixture 11 (Class C fly ash, C/(F+C) = 0.50, W/C = 0.45).

b. Mixture 6 (Class F fly ash, C/(F+C) = 0.40, W/C = 0.40).

A description of the test methods and results are presented in this chapter.

Mechanical Properties Investigation

30. A series of early-time material properties tests was conducted on hardened concrete specimens in support of the calibration and verification of the time-dependent material model to be used in the incremental-construction analysis. Specimens were prepared from Mixtures 6 and 11 for conducting compression tests and creep tests. The results of selected tests conducted on the fresh concrete are given in Table 10. In addition, time-of-setting (TOS) tests were conducted in accordance with ASTM C 403 (ASTM, 1990). Creep tests were conducted at three ages of loading as necessary for the calibration and

Table 10
Results of Tests on Batches of Fresh Concrete
Used for Mechanical Properties Tests

Property	Mixture 6	Mixture 11
Temperature, °F	74	72
Slump, in.*	1-1/4	2-1/2
Air Content, percent*	6.1	6.0
Unit Weight, lbm/ft^3*	142.8	Not Available
Time of Final Setting	9 hr 50 min	14 hr 40 min

* Tests conducted on wet-sieved concrete (<1-1/2-in.)

verification of the time-dependent material model. The ages of loading were chosen as 1, 3, and 14 days.

Compression Tests

31. Compression tests were conducted in accordance with ASTM C 39 (ASTM, 1990) at the ages of 1, 3, 7, 14, 28, 56, 90, 120, and 180 days to provide data on compressive strength as a function of time. In addition, 365-day data will be obtained and will be on file at WES. The specimens tested were 6 in. diameter by 12 in. long. The ends of the specimens tested at ages of 1 day were capped with a neat cement cap, while the specimens tested at ages greater than 1 day were capped with sulfur capping compound. The capped specimens were tested in a 440,000-lbf-capacity, universal testing machine by applying a uniaxial compressive force at 35 psi/sec until the specimen failed. Figure 1 shows the results of these tests for the two mixtures as a function of age. It should be noted that, for Mixture 11, the compressive strengths for these tests are considerably less than the compressive strengths obtained for Mixture 11 in the mixture proportioning study (Table 9). These data tend to suggest a batching error, since normal batch-to-batch variations in the laboratory are not that large. However, after a careful review of laboratory notes from both batches, no hard evidence of an error in batching could be found. A repeat batch of Mixture 11 was cast in the laboratory and tested at ages of 3 and 7 days. Compressive strengths from this batch fell between the two mixtures and were, therefore, inconclusive. Thus, we must assume that the discrepancies are attributable to random variation, since we cannot conclusively prove an error in batching.

32. The elastic modulus of the two mixtures at the various ages of loading was determined from unconfined compression tests in accordance with ASTM C 469 (ASTM, 1990). The compression test cylinders were strain gaged, and stress-strain data were obtained during the tests. An elastic (secant) modulus was obtained from these data. At very early ages (3 days or less), the mixtures exhibited limited linear elastic compressive behavior; however, estimates of elastic modulus at very early times are necessary for calibrating the time-dependent material model. A plot of elastic modulus versus time for the two mixtures is shown in Figure 2.

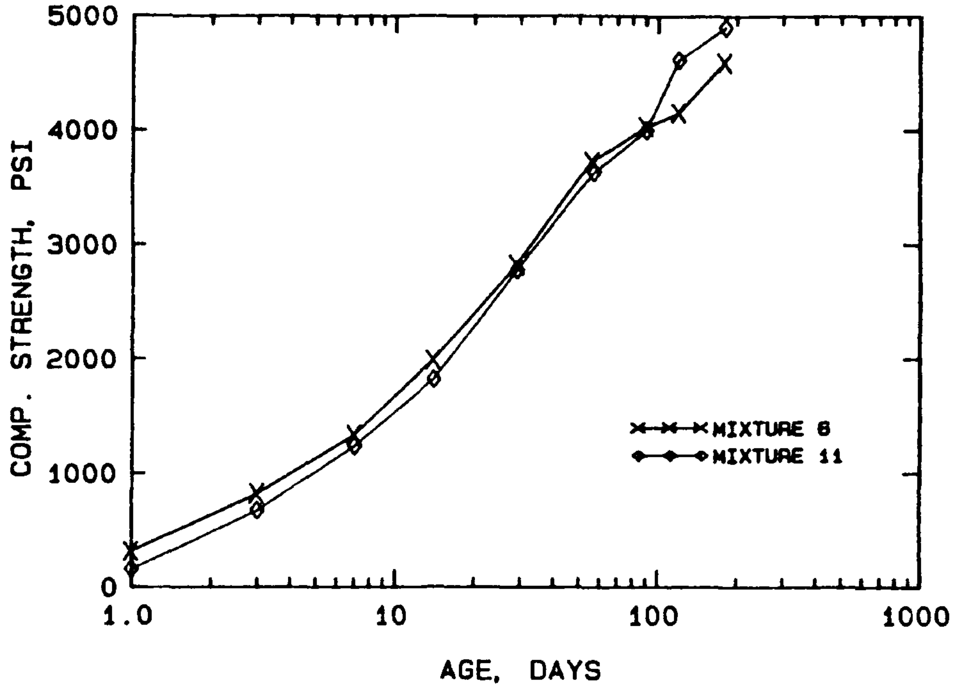

Figure 1. Compressive Strength Development, Creep Test Companion Cylinders

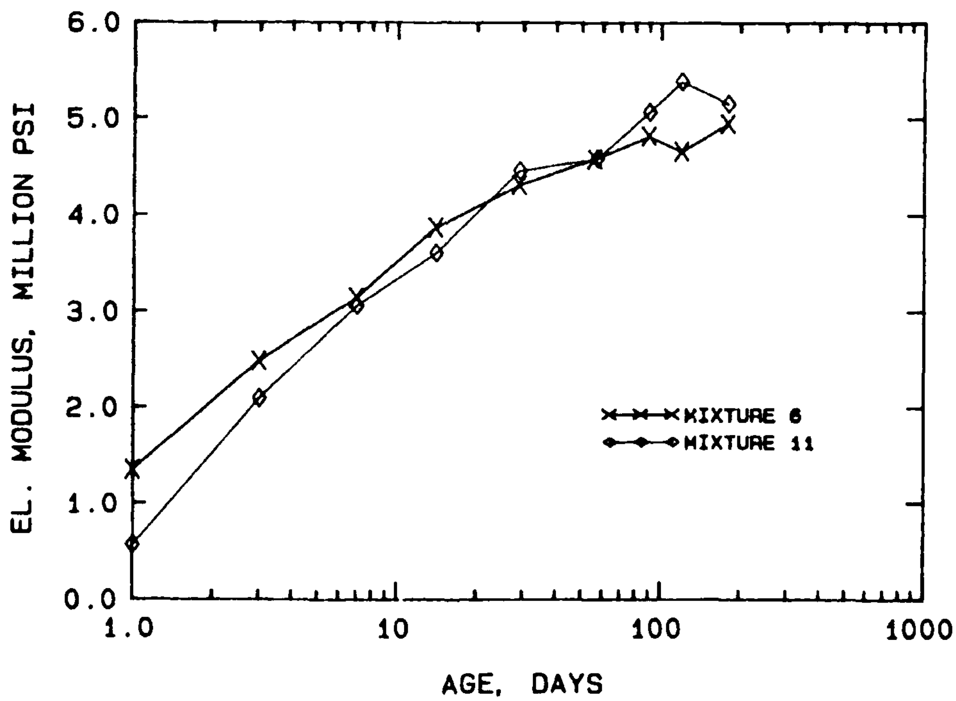

Figure 2. Elastic Modulus Development

Compressive Creep Tests

33. Creep is most simply defined as time-dependent deformation due to sustained load. Creep is normally assumed to be the deformation in excess of shrinkage strains and elastic strains, as shown in Figure 3. A brief discussion of the phenomena measured in a compressive creep test follows.

34. Upon initial application of load at time t_o (Figure 3), the material response is primarily elastic, but may include a nonelastic component. The nominal elastic strain is governed by the elastic modulus at time $t - t_o$. Because the elastic modulus is increasing with time (quite rapidly at early ages), the elastic component of strain decreases with time, labeled as "true elastic strain" in Figure 3. It is common practice to ignore this change in elastic modulus with time except for special applications. This phenomenon is quite important, however, in the calibration of the time-dependent material model for incremental-construction analyses. Shrinkage of the creep specimen is measured by monitoring the deformation of identically prepared unloaded specimens. Thus the creep strains are calculated from the total measured strains as follows:

$$\epsilon_{creep} = \epsilon_{total} - \epsilon_{elastic} - \epsilon_{shrinkage}$$

35. Using these concepts, creep tests were conducted according to ASTM C 512 (ASTM, 1990) modified to include continuous data acquisition by computer. The specimens tested were 6 in. in diameter by 16 in. in length. The creep specimens were cast in steel forms with the longitudinal axis horizontal. These forms accommodated Carlson strain gages placed at the center of the specimens oriented along the longitudinal axis of the cylinder. Steel bearing plates were attached to the ends of the specimen by embedded mechanical anchors. These plates provided a smooth plane surface for applying the compressive force. A bituminous moisture barrier was applied to the surface of the creep specimen immediately after the forms were removed to prevent moisture from entering or leaving the specimen.

36. The apparatus used to perform the creep tests was a hydraulic loading frame designed to maintain a constant stress by means of a gas

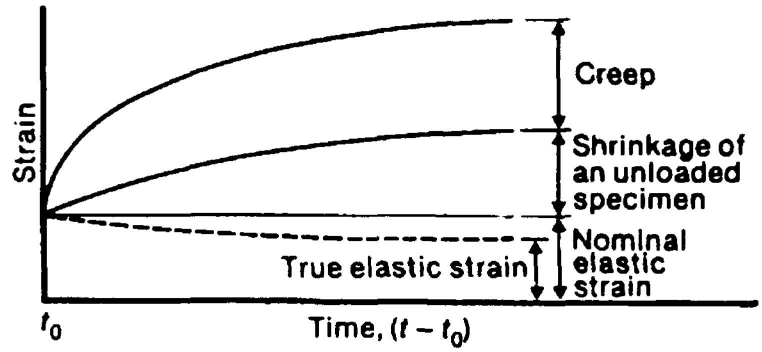

Figure 3. Response of Concrete to Sustained Load

pressure regulator in series with a gas/oil accumulator and hydraulic ram. The desired applied stress was set by means of the gas pressure regulator. The test device accommodated two specimens loaded in series. For each mixture, two control cylinders were also monitored to determine the strains not associated with the applied loads. The creep specimens were loaded to 40 percent of the unconfined compressive strength at the age of loading as determined from unconfined compressive tests on companion 6- by 12-in. cylinders. The following measurements were recorded using a digital data acquisition unit:

a. Applied stress, by pressure transducers located in the gas pressure regulator output line.

b. Strain and temperature in the loaded specimen, by Carlson strain gages embedded in the center of the specimen.

c. Strain and temperature in the control specimen, by Carlson strain gages embedded in the center of the specimen.

d. Time, by an internal clock in the computer data-acquisition unit.

37. The strains recorded by the shrinkage compensation cylinders were subtracted from the measured strains. The elastic strains as a function of time (based upon change in elastic modulus as a function of time) were also subtracted to obtain creep strains. These corrected strains were then

divided by the applied stress to obtain creep strain per unit stress (specific creep).

38. These data are plotted for the two mixtures in Figures 4 and 5. These data show that Mixture 11 experienced significantly more creep, particularly when loaded at 1 day, than did Mixture 6. Because the magnitudes of creep, compressive strength, and elastic modulus all depend upon the degree of hydration, we should expect greater creep strains from Mixture 11 than Mixture 6, since Mixture 11 had a lower elastic modulus and compressive strength at 1, 3, 7, and 14 days than did Mixture 6.

Sealed Length Change

39. The change in length or volume of a concrete specimen sealed to prevent any drying shrinkage has been measured by a number of researchers. In order to simulate the early-age material response properly, this volume-change phenomenon must be included in the material response model.

40. The sealed length change for Mixtures 6 and 11 were measured on 6- by 16-in.-cylindrical specimens identical to the creep specimens. Two specimens were cast at the time of the casting of the other mechanical properties test specimens. The specimens contained an embedded Carlson strain meter embedded at the centroid of the cylinder oriented along the long axis of the cylinder. The cylindrical surfaces of the specimens were sealed to prevent moisture loss with a bituminous moisture barrier; the ends of the specimens were sealed with steel end caps.

41. The specimens were demolded and sealed within minutes of time of final setting of wet-sieved mortar as determined by CRD-C 86. Each specimen was subsequently placed in an INVAR frame which held a linear variable differential transducer (LVDT). These transducers were used to make very precise length change measurements (accuracy = ± 2 microinches) of the concrete cylinder/steel end cap system. These data were used to compare with data obtained from the embedded Carlson strain meters. Figure 6 shows the test configuration.

42. All data were recorded using a digital data acquisition system. The data record began approximately 2 hours after time of final setting. The raw data from both the Carlson gages and LVDT's were adjusted for linear thermal expansion and contraction of the specimen. In the case of the LVDT data, the linear thermal expansion and contraction of the concrete

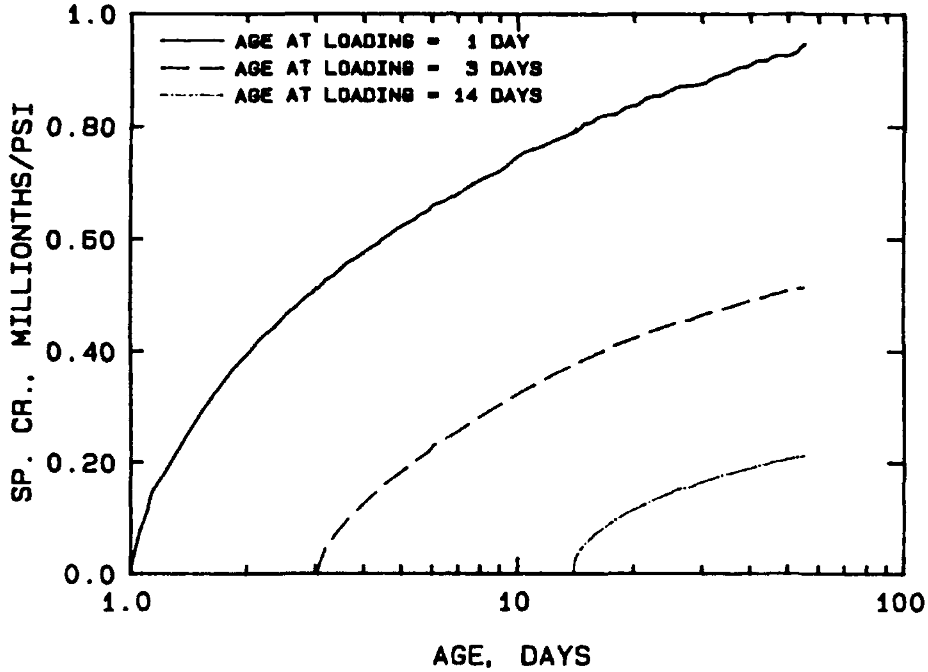

Figure 4. Creep Response, Mixture 6

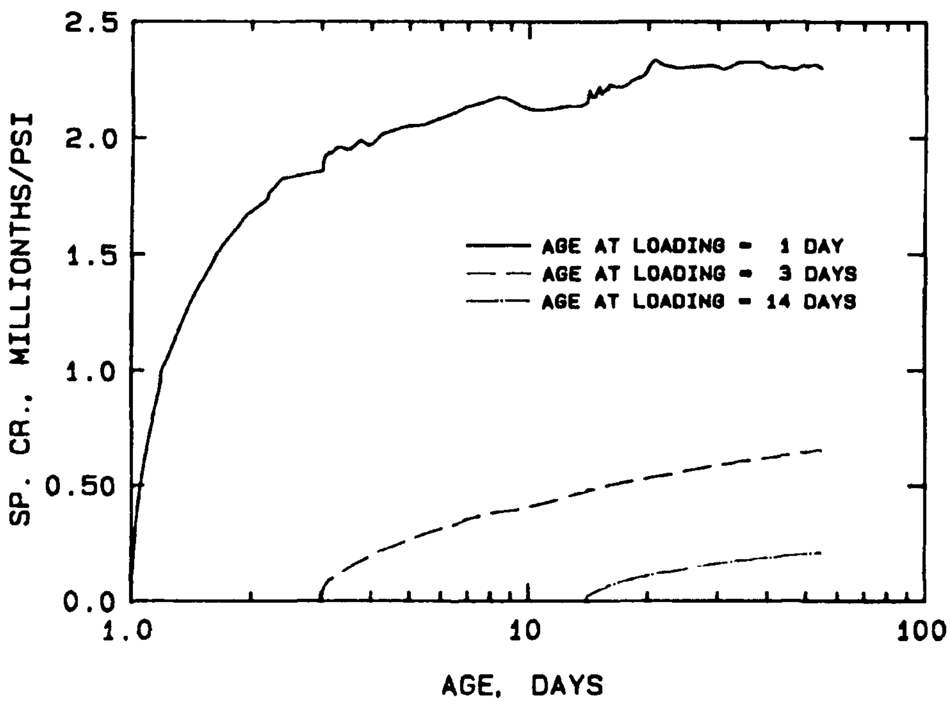

Figure 5. Creep Response, Mixture 11

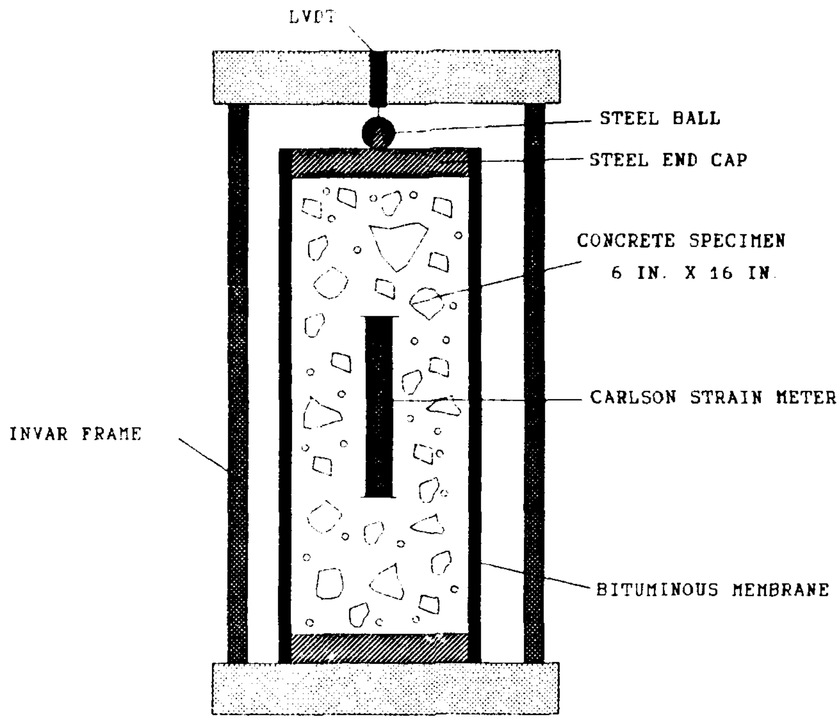

Figure 6. Test Configuration for Sealed Shrinkage Tests

cylinder/steel end caps were subtracted from the raw data. The coefficient of linear thermal expansion of the concrete was determined from the tests described below (CRD-C 39). The coefficient of linear thermal expansion for steel was selected as 6.5 X 10^6 millionths/°F. The temperatures used to correct for the thermal effects were taken from the internal Carlson gages.

43. The results of the sealed length change tests are shown in Figure 7. As can be seen in the figure, Mixture 6 exhibited shrinkage throughout the duration of the test. However, Mixture 11 shows initial expansion followed by a return to near the unstrained condition. This behavior is typical of that exhibited by a concrete made with a shrinkage-compensating cement. To confirm that the data for Mixture 11 were not an aberration, the test was repeated and the data from this repetition are also shown in Figure 7 (labeled "REP" in the figure). These data confirmed the initially observed response of the material. Subsequently, X-ray powder-diffraction techniques were used to examine material from the paste

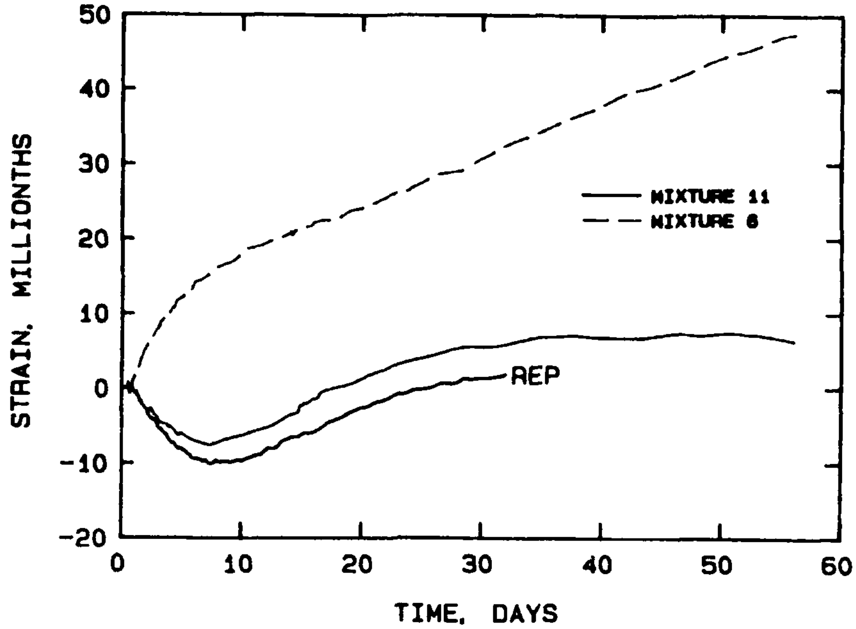

Figure 7. Results of Sealed Shrinkage Tests

portion of both Mixtures 6 and 11 to identify the presence of crystalline compounds which have expansive characteristics. These tests revealed the presence of expansive crystalline phases in Mixture 11 that were not present in Mixture 6. Because the cement and aggregates were common between the two mixtures, the presence of these compounds in Mixture 11 must be attributed to the reaction of the particular cement and Class C fly ash used in this study. This behavior may not be typical of all Class C fly ashes and Type II, HH cements; thus, Class C fly ash from another source may not react with this cement to form a shrinkage-compensating material.

Thermal Properties Investigation

Adiabatic Temperature Rise

44. The temperature rise of the concrete in an adiabatic condition is primarily due to hydration of the cementitious materials. The magnitude and shape of the adiabatic temperature rise versus time curve is an important measure of the heat-generating potential of a concrete mixture. These data are used as the forcing function for the calculation of temperature distributions throughout the structure in an incremental construction analysis.

45. One adiabatic temperature rise test per concrete mixture (Mixtures 6 and 11) was conducted at WES in an adiabatic test facility in accordance with CRD-C 38 (U. S. Army Corps of Engineers, 1990). The specimens were 30-in.-diameter by 29-in.-high cylinders. Each specimen was cast from a single batch of concrete using 3-in. nominal maximum size aggregate. The placement temperatures for the concrete for each mixture was controlled, with the target temperature at or slightly below 60 °F in order to duplicate maximum anticipated field placement temperatures. The tests were conducted for approximately 28 days.

46. The results of the adiabatic temperature rise tests are shown in Figure 8. The placement temperature for Mixture 6 was 56 °F; for Mixture 11, 60 °F. In Table 11, adiabatic temperature rise at selected times are shown for the two mixtures. The results show that the temperature rise for the two mixtures was almost identical for approximately 1 day. The data show that the adiabatic temperature rise curves for the two mixtures are very similar in magnitude throughout the duration of the test. The maximum temperature difference is just under 5 °F at 10 days. At 27 days, the temperature difference is approximately 3.3 °F.

47. Figure 9 shows the instantaneous rate of heat generation (dQ/dt) in Btu/day per pound-mass for the first 5 days. These data show that immediately after casting, there is a high rate of heat generation which falls off rapidly followed by a second, much broader peak at about 1/2 day. This second peak is broader for Mixture 6 than for Mixture 11. This broader peak leads to a slightly greater adiabatic temperature rise for Mixture 6 at times between 1 and 4-1/2 days. However, for times greater than approximately 1-1/2 days, Mixture 11 has a greater rate of heat generation than does Mixture 6. This causes the adiabatic temperature rise of Mixture 11 to surpass the adiabatic temperature rise of Mixture 6 at times greater than approximately 4-1/2 days. Although not shown in Figure 9, the rate of heat generation for the two mixtures is approximately equal at times greater than 10 days; therefore, the adiabatic temperature rise curves are nearly parallel after approximately 10 days.

Table 11

Selected Adiabatic Temperature Rise Data

Time, days	Adiabatic Temperature Rise, °F		
	Mixture 6	Mixture 11	Difference (Mixture 6 - Mixture 11)
0.00	0.00	0.00	0.00
0.50	6.46	5.96	0.50
1.00	16.13	11.79	4.34
3.00	26.57	23.85	2.72
4.52	29.45	29.45	0.00
7.00	32.52	35.41	-2.89
10.00	35.06	39.89	-4.83
14.00	37.86	42.58	-4.72
17.50	39.57	43.68	-4.11
21.00	40.53	44.42	-3.89
24.00	41.38	44.91	-3.53
27.00	41.99	45.30	-3.31
28.00	42.15	-----	-----

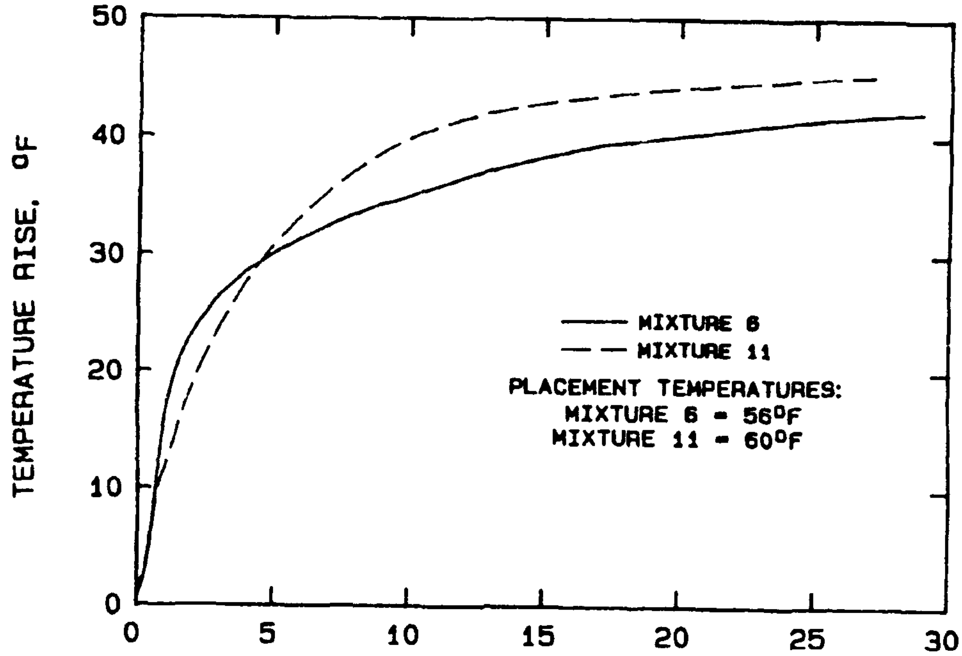

Figure 8. Adiabatic Temperature Rise

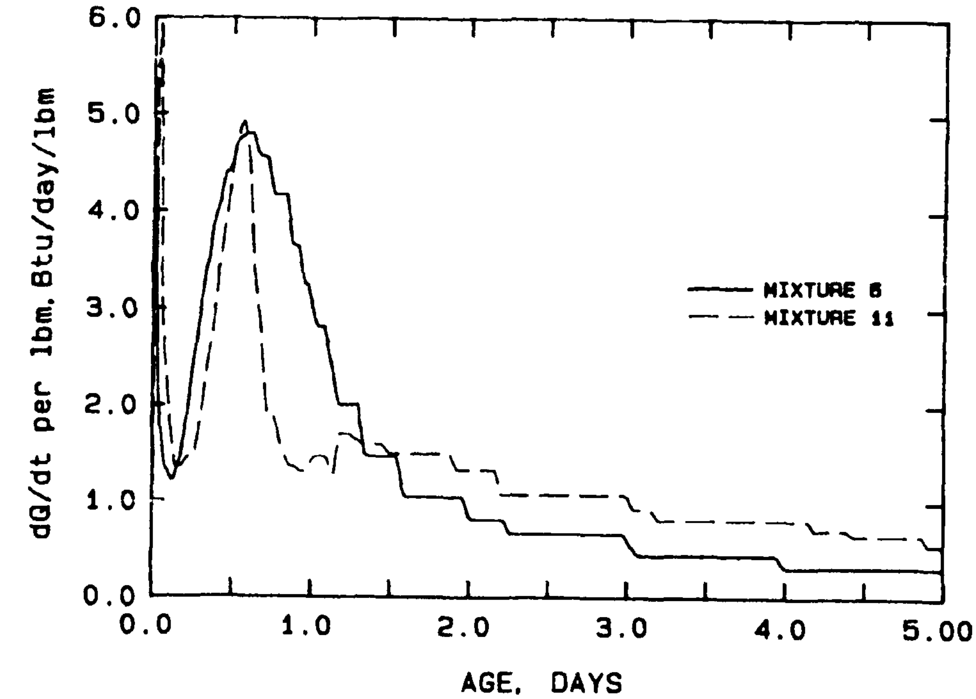

Figure 9. Instantaneous Rate of Heat Generation

Other Thermal Properties

48. The coefficient of linear thermal expansion, thermal diffusivity, specific heat, and thermal conductivity of concrete from Mixtures 11 and 6 were determined at approximately 28 days on laboratory molded specimens. The results of these tests are reported below.

49. The coefficient of linear thermal expansion was determined in accordance with CRD-C 39-81 (US Army Corps of Engineers, 1990) at a test age of approximately 28 days. Two 8- by 16-in.-cylindrical specimens (with 3-in. maximum nominal size aggregate) were cycled between water baths maintained at 40 and 100 °F. The strains and temperatures in the specimens were measured with embedded Carlson strain meters. These meters were located at the centroid of the specimen and oriented along the longitudinal axis of the cylinders. The temperatures of the water baths were measured with thermocouples placed in the water. All data, including the temperatures of the water baths, were acquired and recorded with a digital data acquisition system and microcomputer. The results of the tests are tabulated in Tables 12 and 13 for Mixtures 6 and 11, respectively.

50. The thermal diffusivity of each of the two mixtures at an age of approximately 28 days was determined in accordance with CRD-C 36-73 (US Army Corps of Engineers, 1990) on 8- by 16-in.-cylindrical specimens. However, the temperature of the hot and cold water baths was maintained at 140 °F and 40 °F, respectively, rather than maintaining the hot bath at a temperature of 212 °F and the cold bath at essentially the temperature of the laboratory tap water as called for in the standard method. This range of temperatures was chosen because it is the likely range of temperatures expected in the mass concrete. The water bath temperatures were monitored with thermocouples. The specimen temperatures were monitored with thermocouples placed in the center of gravity of the cylindrical concrete specimens. All data were acquired and recorded using a digital data acquisition system and microcomputer. Two specimens of a given mixture were simultaneously alternated between the hot and cold baths. The specimens were allowed to remain in the bath until the temperature at the center of the specimen equilibrated with the bath temperature. The results of the tests are tabulated in Tables 14 and 15 for Mixtures 6 and 11, respectively.

Table 12
Results of Linear Coefficient of Thermal Expansion Tests, Mixture 6

<u>Specimen 1</u>

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Coefficient of Linear Thermal Expansion, millionths/°F
1	100	40	3.727
2	40	100	3.763
3	100	40	3.788
4	40	100	3.850
5	100	40	3.734
6	40	100	3.817
	Mean		3.780

<u>Specimen 2</u>

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Coefficient of Linear Thermal Expansion, millionths/°F
1	40	100	3.940
2	100	40	3.820
3	40	100	3.904
4	100	40	3.947
5	40	100	4.027
6	100	40	3.869
	Mean		3.918
	Grand Mean		3.849

Table 13
Results of Linear Coefficient of Thermal Expansion Tests, Mixture 11

Specimen 1

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Coefficient of Linear Thermal Expansion, millionths/°F
1	100	40	3.588
2	40	100	3.644
3	100	40	3.586
4	40	100	3.679
5	100	40	3.628
6	40	100	3.709
	Mean		3.639

Specimen 2

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Coefficient of Linear Thermal Expansion, millionths/°F
1	40	100	4.019
2	100	40	3.940
3	40	100	4.009
4	100	40	3.982
5	40	100	4.021
6	100	40	3.932
	Mean		3.984
	Grand Mean		3.811

Table 14
Results of Thermal Diffusivity Tests, Mixture 6

Specimen 1

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Thermal Diffusivity, ft^2/hr
1	100	40	0.0350
2	40	100	0.0322
3	100	40	0.0354
4	40	100	0.0331
5	100	40	0.0356
6	40	100	0.0327
7	100	40	0.0349
8	40	100	0.0324
	Mean		0.0339

Specimen 2

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Thermal Diffusivity, ft^2/hr
1	40	100	0.0313
2	100	40	0.0340
3	40	100	0.0312
4	100	40	0.0350
5	40	100	0.0320
6	100	40	0.0348
7	40	100	0.0322
8	100	40	0.0354
9	40	100	0.0318
10	100	40	0.0345
	Mean		0.0332
	Grand Mean		0.0335

Table 15
Results Thermal Diffusivity Tests, Mixture 11

Specimen 1

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Thermal Diffusivity, ft^2/hr
1	100	40	0.0328
2	40	100	0.0361
3	100	40	0.0361
4	40	100	0.0358
5	100	40	0.0368
6	40	100	0.0351
7	100	40	0.0384
8	100	40	0.0378
	Mean		0.0361

Specimen 2

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Thermal Diffusivity, ft^2/hr
1	40	100	0.0324
2	100	40	0.0362
3	40	100	0.0326
4	100	40	0.0349
5	40	100	0.0323
6	100	40	0.0361
7	40	100	0.0326
8	40	100	0.0321
	Mean		0.0337
	Grand Mean		0.0349

51. The specific heats of the two concrete mixtures were determined at an age of approximately 28 days in accordance with CRD-C 124-73 (U. S. Army Corps of Engineers, 1990). These tests were conducted on samples containing 3-in. maximum nominal size aggregates obtained from 8- by 16-in. cylinders. In addition, the specific heat was determined for Mixture 11 using a sample obtained from a 6- by 12-in. cylinder containing a wet-sieved concrete (1-1/2-in. maximum nominal size aggregate). The specific heat of the limestone aggregate was also obtained on a sample of 1-1/2-in. maximum nominal size aggregate. As noted for the thermal diffusivity tests, the hot and cold water bath temperatures were maintained at 100 °F and 40 °F, respectively, rather than at 125 °F and 35 °F as prescribed in CRD-C 124. All temperatures were measured with a precision thermistor thermometer. The results of the tests are given in Tables 16 through 18.

52. The thermal conductivity of the concrete was calculated in accordance with CRD-C 44-63 (U. S. Army Corps of Engineers, 1990). This method requires the results of the thermal diffusivity and specific heat tests as reported above. Also required is the actual unit weight of the concrete. This was determined by weighing the concrete specimens in air and water. The thermal conductivities of the two mixture were as follows:

Mixture	Thermal Conductivity, Btu/hr-ft^2-°F
6	1.076
11	1.121

Table 16
Results of Specific Heat Tests, Mixture 11

3-in. Maximum Nominal Size Aggregate

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Specific Heat, BTU/lb-°F
1a	40	100	0.216
2a	40	100	0.215
3a	40	100	0.218
4a	40	100	0.221
	Mean		0.218
1b	100	40	0.220
2b	100	40	0.220
3b	100	40	0.220
4b	100	40	0.223
	Mean		0.221
	Grand Mean		0.219

Moisture Content = 3.6 percent
Unit Weight = 152.9 lbm/ft^3

Table 17
Results of Specific Heat Tests, Mixture 11

3-in. Maximum Nominal Size Aggregate

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Specific Heat, BTU/lb-°F
1a	40	100	0.213
2a	40	100	0.219
	Mean		0.216
1b	100	40	0.221
2b	100	40	0.221
	Mean		0.221
	Grand Mean		0.219

1-1/2-in. Maximum Nominal Size Aggregate

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Specific Heat, BTU/lb-°F
1a	40	100	0.227
2a	40	100	0.230
	Mean		0.229
1b	100	40	0.228
2b	100	40	0.227
	Mean		0.228
	Grand Mean		0.228

Table 18
Results of Specific Heat Tests,
1-1/2-in. Maximum Nominal Size Limestone Aggregates

Cycle Number	Nominal Starting Temperature, °F	Nominal Final Temperature, °F	Specific Heat, BTU/lb-°F
1a	40	100	0.207
2a	40	100	0.209
3a	40	100	0.210
	Mean		0.209
1b	100	40	0.208
2b	100	40	0.209
3b	100	40	0.208
	Mean		0.208
	Grand Mean		0.209

Moisture Content = 0.97 percent
Unit Weight = 152.9 lbm/ft^3

PART V: CALIBRATION AND VERIFICATION OF THE TIME-DEPENDENT, VISCO-ELASTIC MATERIAL MODEL

General

53. In order to accurately model the field construction process, the incremental construction analysis procedure requires that several material-specific parameters be mathematically described. These parameters are input either as constants or as algebraic functions of time. This process of mathematically describing the material response features in the model is referred to as the model calibration procedure. In the case of the time-dependent visco-elastic material model, an additional step is required. After calibrating the aging visco-elastic material model (UMAT subroutine), the UMAT subroutine is used in a finite-element analysis procedure (ABAQUS) to model the suite of creep tests performed on the concrete and verify that the response of the material is being reasonably predicted. The calibration and verification procedures for the time-dependent material model are described below. A more complete description of the aging, visco-elastic material model and the calibration procedures for the model are given by Garner and Hammons (in preparation).

Calibration

54. The time-dependent visco-elastic (creep) model (UMAT) used in the analysis was calibrated for Mixtures 6 and 11. Information required for calibration included 3-day creep compliance, shrinkage, and elastic modulus as a function of time. Calibration of the model for creep and elastic strains is a two-part process. The creep compliance (as determined from a 3-day creep test) given by an equation of the form

$$C(t) = A_1[1 - e^{r_1(t-t_o)}] + A_2[(1 - e^{r_2(t-t_o)}] + A_3[(1 - e^{r_3(t-t_o)}]$$

$$\text{for } t \geq t_o \text{ days}$$

where

t = age of the concrete in days

t_o = age at loading in days

$C(t)$ = in./in. per psi

The parameters A_1, A_2, A_3, r_1, r_2, and r_3 are determined by trial and error fit to test data. The form of the time-dependent elastic modulus equation is

$$E(t) = E_1[1 - e^{x_1(t-1)}] + E_2[1 - e^{x_2(t-1)}] + E_3[1 - e^{x_3(t-1)}] + E(1)$$

$$\text{for } t \geq 1 \text{ day}$$

where E_1, E_2, E_3, x_1, x_2, and x_3 are constants determined from a trial and error fit to test data, $E(1)$ is the one-day elastic modulus, t is age of the concrete in days, and $E(1)$ and $E(t)$ are in psi.

55. Elastic modulus data from the material properties tests were used to determine the values of the unknown constants in the modulus equation. For Mixture 11, the values were

$E_1 = 2.86025 \times 10^6$ $\qquad$ $x_1 = -5.95317 \times 10^{-2}$

$E_2 = 2.63161 \times 10^6$ $\qquad$ $x_2 = -8.83053 \times 10^{-1}$

$E_3 = -9.77554 \times 10^5$ $\qquad$ $x_3 = -2.64916$

$E(1) = 0.57 \times 10^6$ psi

For Mixture 6, the values were

$E_1 = 2.06998 \times 10^6$ $\qquad$ $x_1 = -5.95317 \times 10^{-2}$

$E_2 = 1.13274 \times 10^6$ $\qquad$ $x_2 = 4.07563 \times 10^{-1}$

$E_3 = 2.77627 \times 10^5$ $\qquad$ $x_3 = -2.64916$

$E(1) = 1.35 \times 10^6$ psi

Plots of the modulus data versus algebraic model for the two mixtures are shown in Figures 10 and 11.

56. Constants in the creep compliance function for the two concrete mixtures were determined using 3-day creep test data. For Mixture 11, the values substituted in the creep compliance curve were as follows:

$A_1 = 0.39486 \times 10^{-6}$ $\qquad$ $r_1 = -5.298 \times 10^{-2}$

$A_2 = 0.22632 \times 10^{-6}$ $\qquad$ $r_2 = -6.623 \times 10^{-1}$

$A_3 = 0.12595 \times 10^{-6}$ $\qquad$ $r_3 = -2.649$

For Mixture 6, the values were as follows:

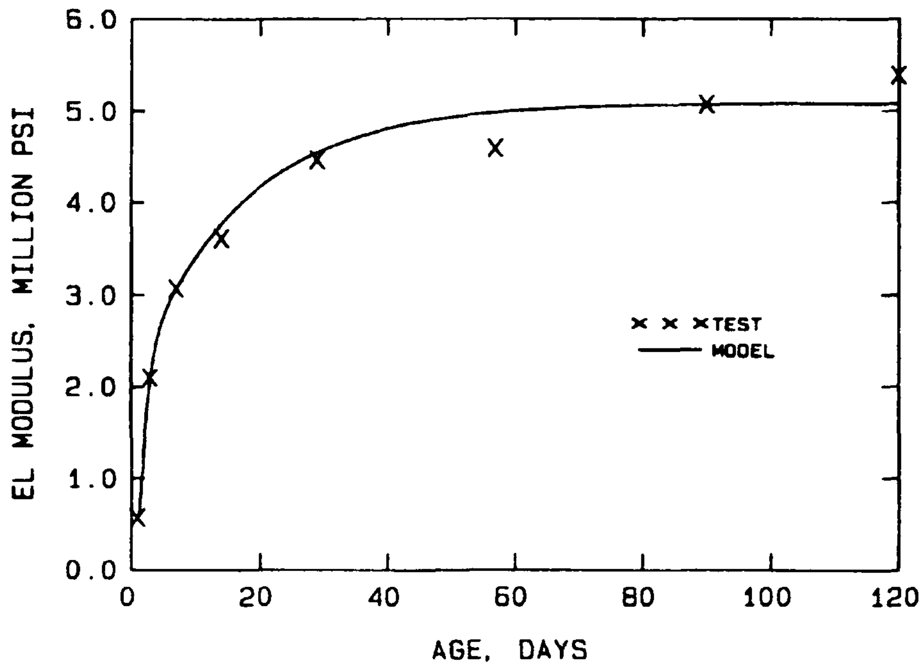

Figure 10. Comparison of Test Data with Model, Elastic Modulus, Mixture 11

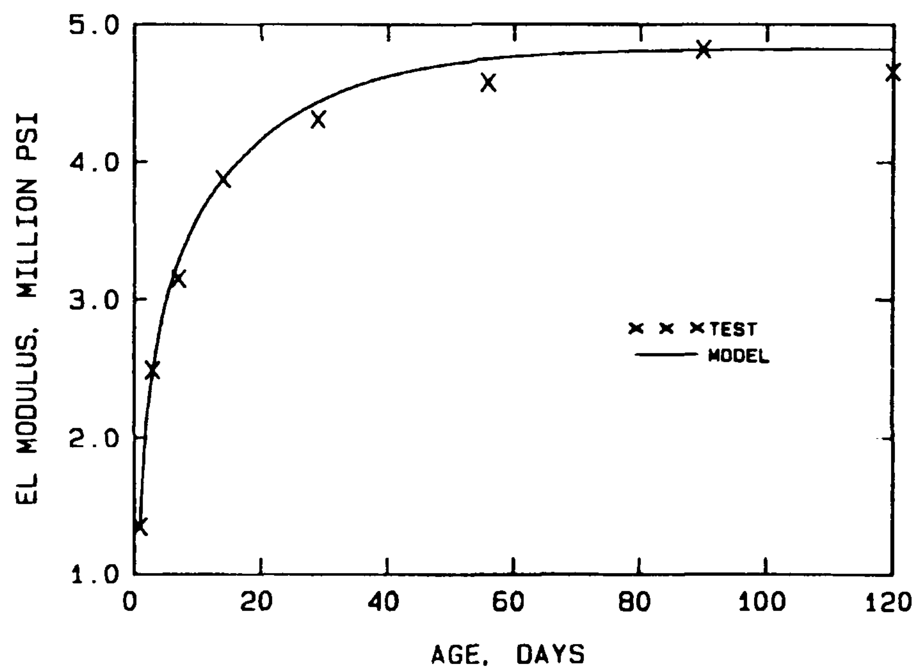

Figure 11. Comparison of Test Data with Model, Elastic Modulus, Mixture 6

$A_1 = 0.32157 \times 10^{-6}$ $r_1 = -0.3532$

$A_2 = 0.16326 \times 10^{-6}$ $r_2 = -0.4415$

$A_3 = 0.09270 \times 10^{-6}$ $r_3 = -0.1352$

Plots of the above equations with test data are shown in Figures 12 and 13.

57. To account for the volumetric changes that occur during the hydration process, the UMAT material model includes an equation of the form

$$\epsilon_{shrinkage} = S_1(1 - e^{z_1 t}) + S_2(1 - e^{z_2 t})$$

where $\epsilon_{shrinkage}$ has units of in./in. and t is time since casting in days. For Mixture 6, the values of the four terms in the equation were determined graphically as follows:

$S_1 = 58.69 \times 10^{-6}$ $z_1 = -0.02649$

$S_2 = 9.46 \times 10^{-6}$ $z_2 = -0.5298$

Because Mixture 11 was essentially shrinkage-compensated, shrinkage need not be included in the analyses. Any value of shrinkage assumed would be conservative for the analyses. Plots of these results are shown in Figure 14.

Verification

58. The model, incorporating these curves, was then used with ABAQUS to simulate the entire suite of creep tests for each mixture. Each creep cylinder was modeled using a single axisymmetric element supported on rollers at boundaries and uniformly loaded across the top surface (Figure 15). The results of these runs were then plotted against actual test data for comparison. Results of the verification analyses for Mixtures 6 and 11 are shown in Figures 16 and 17. The model duplicates the test data reasonably well at ages 3 and 14 days. However, at 1 day the model under predicts strains. This problem has been noted with the model previously and appears to be a fundamental problem related to the aging formulation in the model. However, with the current model, the calibration obtained is the near optimal and is considered acceptable.

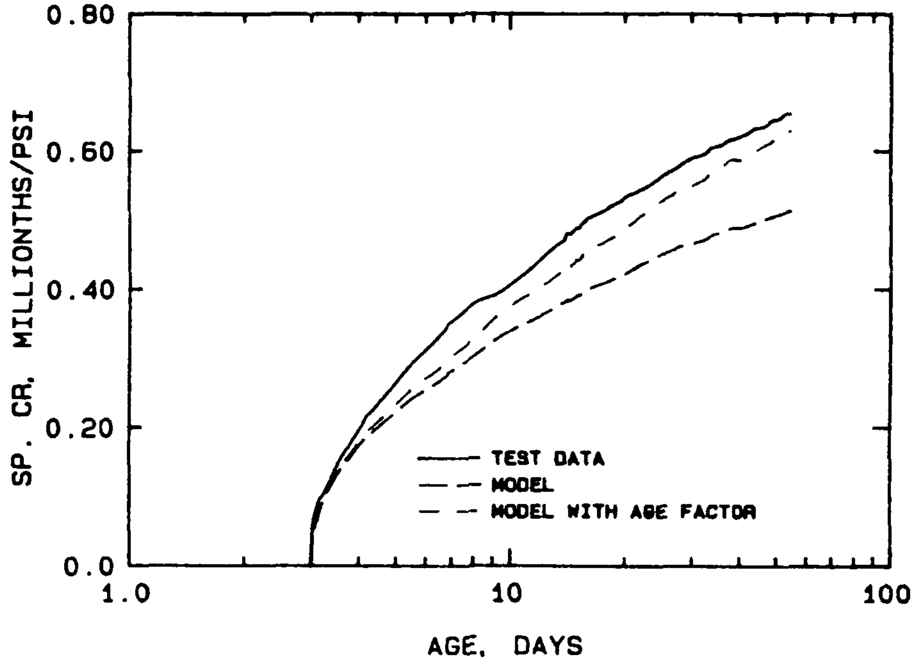

Figure 12. Comparison of Test Data with Model, 3-Day Specific Creep, Mixture 11

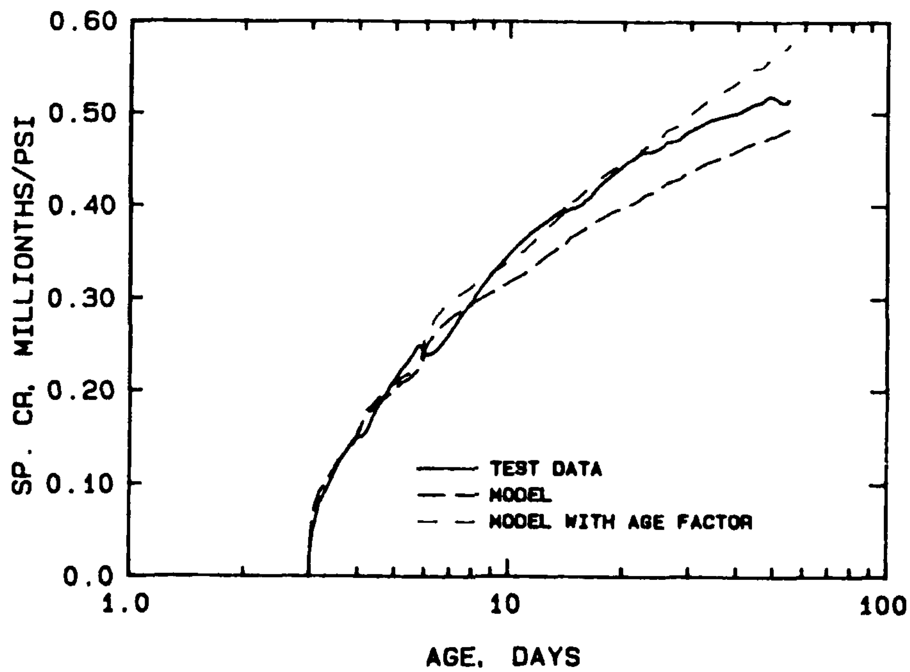

Figure 13. Comparison of Test Data with Model, 3-Day Specific Creep, Mixture 6

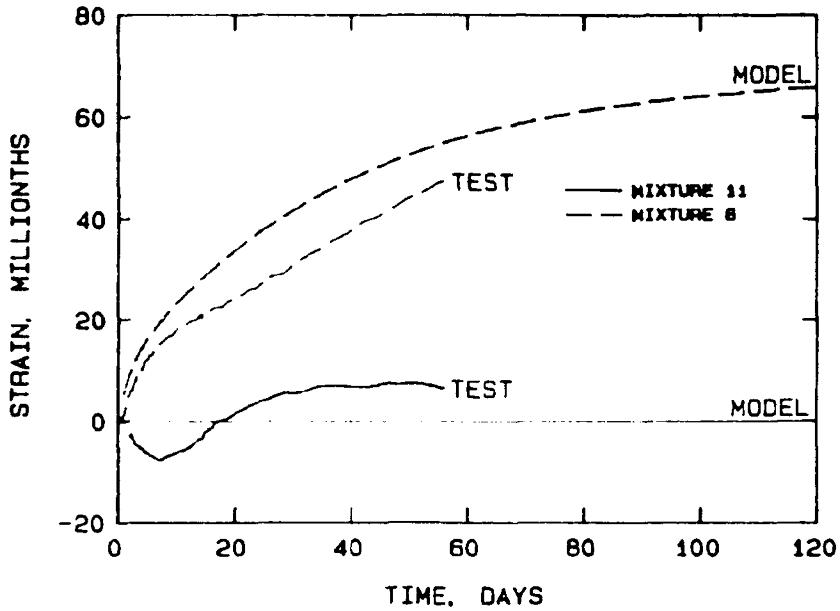

Figure 14. Comparison of Model with Shrinkage Data

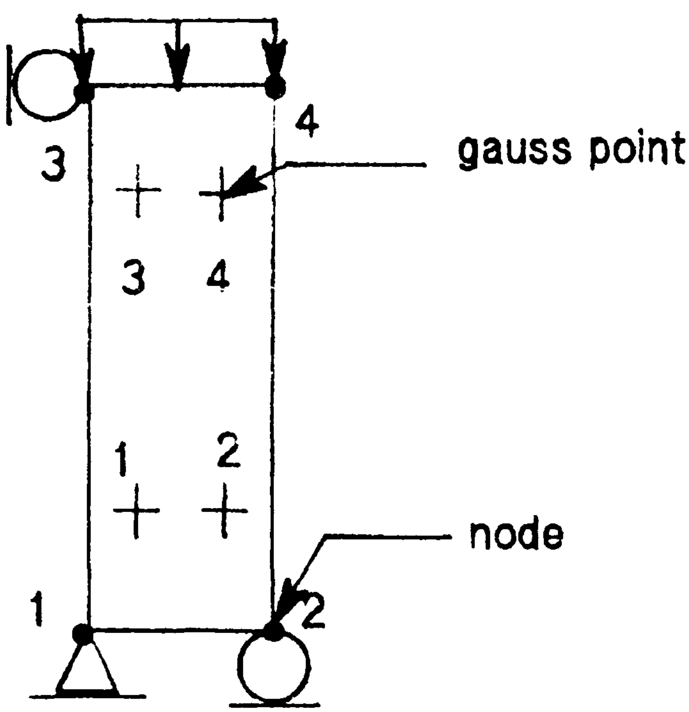

Figure 15. Finite Element Model for Creep Test Simulation

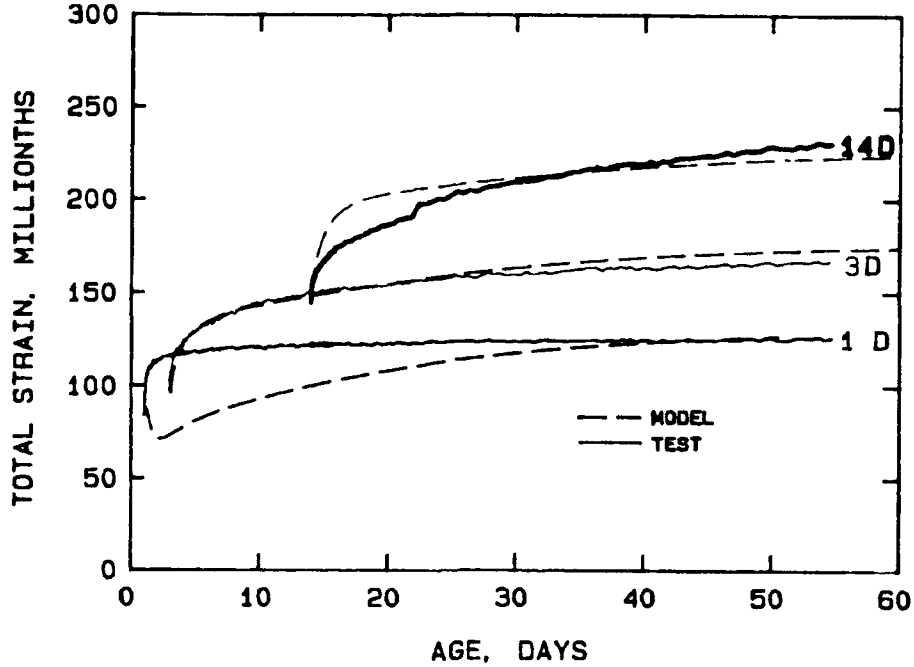

Figure 16. Comparison of ABAQUS Results with Test Data, Mixture 11

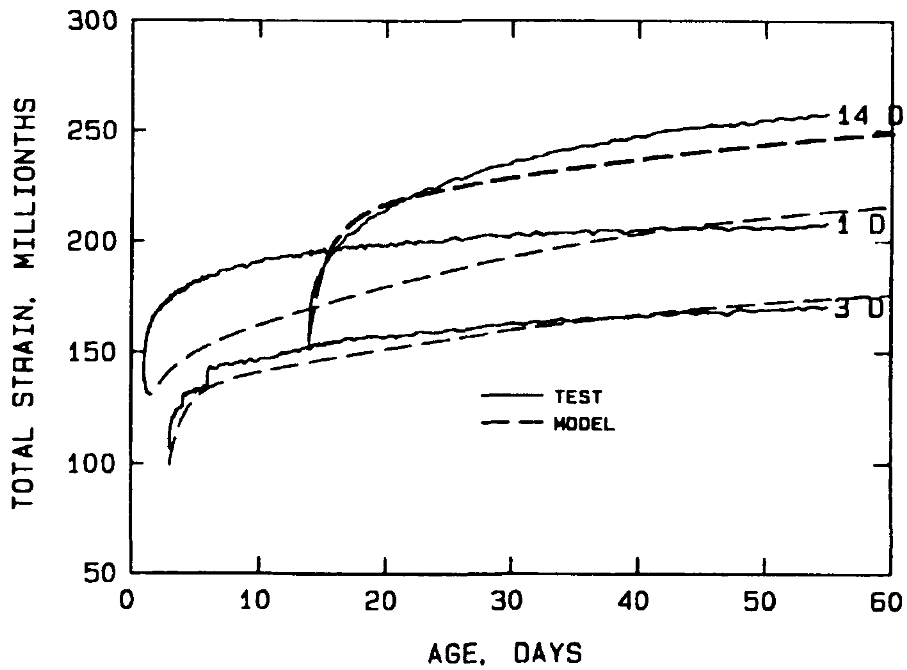

Figure 17. Comparison of ABAQUS Results with Test Data, Mixture 6

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

59. The materials used in this study were selected by the Louisville District based upon information of available sources to be typical of those likely to be selected by a contractor for construction of the Olmsted Locks and Dam. A Type II, low-alkali, cement with a heat of hydration requirement of 70 cal/gm at 7 days was used. One Class C and three Class F fly ashes were evaluated using paste and mortar specimens. From this study, one Class F fly ash and the Class C fly ash were selected for preparation of trial concrete mixtures. The large aggregate was 3-in. nominal maximum size limestone, and natural river sand was used for the fine aggregate.

60. A matrix of 12 trial concrete mixtures with levels of replacement of cement with fly ash of up to 50 percent (i.e., ratios of fly ash to total cementitious materials by volume, C/(F+C), of up to 50 percent) for Class C fly ash and up to 40 percent for Class F fly ash were proportioned and batched in the laboratory. Total theoretical cementitious materials content (by volume) ranged from 3.02 to 3.83 94-lbm bag equivalents per cubic yard. These mixtures were proportioned to meet the project requirements for water-cement ratio, slump, air content, and to minimize early-time heat generation. The mixtures were evaluated on the basis of average compressive strength requirements of at least 500 psi at 2 days and 3,900 psi at 120 days along with economy.

61. Results of unconfined compression tests on the 12 mixtures demonstrate that mixture proportions with both Class C and Class F fly ashes can be selected to produce strengths at 120 days that meet the project requirements of 3,900 psi. Compressive strengths well in excess of 500 psi at 2 days can be obtained by the same mixtures.

62. From the matrix of 12 trial concrete mixtures, two mixtures were chosen for complete thermal and mechanical characterization:

<u>a</u>. Mixture 6 (Class F fly ash, W/C = 0.40, C/(F+C) = 0.40).

<u>b</u>. Mixture 11 (Class C fly ash, W/C = 0.45, C/(F+C) = 0.50).

For the two mixtures, relationships of compressive strength and elastic modulus as a function of time, compressive creep at early ages, and sealed shrinkage were determined in the laboratory.

63. This work confirms that magnitudes of creep at early ages are closely related to the degree of hydration of the cementitious materials. Concrete mixtures containing high levels of fly ash (which tend to hydrate slowly compared to pure portland-cement concretes) experience more creep at early ages than those mixtures which tend to hydrate more rapidly. Because high magnitudes of creep strain are beneficial in reducing thermal stresses, high levels of fly ash appear to be beneficial.

64. The thermal properties determined in this investigation (coefficient of linear thermal expansion, thermal diffusivity, specific heat, and thermal conductivity) were in the range of published values for limestone aggregate concretes.

65. Adiabatic temperature rises for both the Class C and Class F are very similar in magnitude and shape for the mixture proportions chosen. Therefore, concrete mixtures meeting the compressive strength requirement using either Class C or Class F fly ash should have comparable heat-generating potential. Thus the choice of a Class C or Class F fly ash should have a minimal effect on the total heat generated if the mixture proportions are selected prudently to attain the required strength.

66. The Class C fly ash chosen for this study in combination with the Type II, HH cement chosen for this study react in a shrinkage-compensating manner. This behavior may not be true for other Class C fly ashes or other Type II, HH cements.

Recommendations

67. It is recommended that the mechanical and thermal properties developed in this investigation be used to conduct incremental construction analyses for Olmsted Locks and Dam. Recommended values or mathematical expressions as a function of time in days for both Mixture 6 (Class F fly ash) and Mixture 11 (Class C fly ash) are given in Table 19.

68. At the time of this investigation, project materials were not known. When actual project materials are selected, the results of this study should be reevaluated by a materials engineer to determine the effects of

differences in materials on the thermal and mechanical properties published in this report. Additional testing may be necessary to ascertain the effects of project materials on material properties and incremental construction analyses.

Table 19
Recommended Value or Expression for Finite Element Analyses

Parameter	Recommended Value or Expression for Use in Finite Element Analyses	
	Mixture 6 (Class F Fly Ash)	Mixture 11 (Class C Fly Ash)
Coefficient of Linear Thermal Expansion, millionths/°F	3.849	3.811
Specific Heat, Btu/lbm-°F	0.219	0.219
Thermal Diffusivity, ft^2/hr	0.0335	0.0349
Thermal Conductivity, Btu/ft-hr-°F	1.076	1.121
Elastic Modulus*, psi for $t \geq 1$ day	$\{2.06998[1 - \exp(-0.0595317(t-1))] + 1.13274[1 - \exp(-0.407563(t-1))] + 0.277627[1 - \exp(-2.64916(t-1))] + 1.35\} \times 10^6$	$\{2.86025[1 - \exp(-0.0595317(t-1))] + 2.63161[1 - \exp(-0.883053(t-1))] - 0.977554[1 - \exp(-2.64916(t-1))] + 0.57\} \times 10^6$
3-Day Specific Creep*, millionths/psi for $t \geq 3$ days	$0.32157[1 - \exp(-0.3532(t-3))] + 0.16326[1 - \exp(-0.4415(t-3))] + 0.09270[1 - \exp(-0.1325(t-3))]$	$0.39486[1 - \exp(-0.05298(t-3))] + 0.22632[1 - \exp(-0.6623(t-3))] + 0.12595[1 - \exp(-2.649(t-3))]$
Shrinkage*, millionths for $t \geq 0$ days	$58.69[1 - \exp(-0.02649t)] + 9.46[1 - \exp(-0.5298t)]$	0

* Expressed as a function of time, t, in days.

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